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Correlation of Nocturnal Thunderstorms and Boundary-Layer Convergence

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ABSTRACT—An analysis is made of 11 Great Plains nocturnal thunderstorm occurrences that have no obvious synoptic scale support. The pressure patterns and local terrain configurations are input to a numerical boundary-layer model that computes the vertically integrated boundary-layer convergence. The time and space phasing of the vertical velocities thus obtained are in good agreement with the time and space phasing of all 11 thunderstorm occurrences for the beginning of the activity, but they are acceptable in only 6 cases for the termination of the activity. There is a tendency for the model to forecast boundary-layer convergence where no thunderstorms occur; but in many such cases, stability and humidity data are unfavorable for thunderstorm activity.

1. INTRODUCTION

In general, thunderstorms not associated with frontal activity exhibit a tendency for maximum occurrence in the afternoon hours when lapse rates over land tend to be steep because of surface heating. It is, therefore, somewhat surprising to find that over certain land areas thunderstorms occur predominantly at night. The region centered roughly over eastern Nebraska and Iowa is one such area. The most plausible explanation for this phenomenon is that the local terrain assumes the form of a broad valley into which drainage convergence, accompanied by rising motion in the central portion of the valley, occurs at night (Means 1952).

Verification of this explanation using actual wind data is difficult since winds are routinely measured at only about four levels below 2 km, and since the divergent component of the wind is often smaller than errors associated with the measurements and data representativeness. Nevertheless, several investigators have obtained evidence corroborating a connection between boundary-layer rising motions and thunderstorm occurrence (Bleeker and Andre 1951, Curtis and Panofsky 1958, Pitchford and London 1962, Bonner 1966).

One purpose of this article is to further investigate the possibility that nocturnal thunderstorm activity might be caused by boundary-layer convergence; actual pressure data and a refinement of the Ekman-layer theory are used. The simplest version of the Ekman theory states that friction-induced boundary-layer convergence is proportional to the geostrophic vorticity. The advantage of using such a theory is that the geostrophic vorticity is much better determined than the horizontal convergence pattern. The chief disadvantage is that this theory is not immediately applicable in a strongly time-dependent and horizontally nonuniform atmosphere. An earlier paper (Paegle and Rasch 1973, hereafter referred to as I) shows that diurnal oscillations of eddy stresses and of buoyancy forces above the terrain slopes of the Great Plains cause significant deviations from the steady linear Ekman solutions. The boundary-layer model described in I will be used in conjunction with the pressure and terrain data of 11 cases of nocturnal thunderstorm activity to compute boundary-layer-induced convergence and rising motions.

Nine of the 11 cases had no thunderstorm activity in the region the previous afternoon and the activity dissipated by shortly after sunrise. In the other two cases, activity that existed the previous afternoon greatly intensified during the night and then weakened the next morning. These fluctuations of activity were not accompanied by any apparent synoptic scale flow variation, and all selected situations except one were nonfrontal in nature. In the exception, frontolysis was occurring in the vicinity of the activity.

Section 2 presents an abbreviated description of the boundary-layer model used to compute the rising motions. In reference I, it is shown that this model predicts certain climatological features of low-level jets. A major purpose of this article is to ascertain whether its vertical motion predictions correlate well with individual anomalous nocturnal thunderstorm occurrences. Section 3 describes the case selections and computational procedures used to obtain the necessary pressure and terrain data for the boundary-layer model. Section 4 describes one particular period of study in detail, and section 5 summarizes the forecast accuracy of the model for all 11 cases studied.

2. BOUNDARY-LAYER MODEL

The model equations are

$$\frac{\partial u}{\partial t}+uu_x+vu_y+wu_z-fv=-fv_g+(Ku_z)_z, \tag{1}$$

$$\frac{\partial v}{\partial t}+uv_x+vv_y+wv_z+fu=fu_g+(Kv_z)_z, \tag{2}$$

$$\frac{\partial u_x}{\partial t}+u_x u_x+v_x u_y+w u_{xz}-f v_x=-f v_{gx}+(K u_{xz})_z, \qquad (3)$$

$$\frac{\partial v_x}{\partial t}+u_x v_x+v_x v_y+w v_{xz}+f u_x=f u_{gx}+(K v_{xz})_z, \qquad (4)$$

$$\frac{\partial u_y}{\partial t}+u_y u_x+v_y u_y+w u_{yz}-f v_y=f v_{gy}+(K u_{yz})_z, \qquad (5)$$

$$\frac{\partial v_y}{\partial t}+u_y v_x+v_y v_y+w v_{yz}+f u_y=f u_{gy}+(K v_{yz})_z, \qquad (6)$$

and

$$u_x+v_y+w_z=0. \qquad (7)$$

In these equations, u, v and u_g, v_g denote eastward and northward components of the actual and geostrophic winds. Subscripts x, y, and z denote partial differentiations with respect to x, y, and z. The Coriolis parameter is denoted by f, time by t, vertical velocity by w, and the turbulent vertical momentum fluxes by $K\partial u/\partial z$ and $K\partial v/\partial z$. Equations (3) and (5) are obtained by x and y differentiations, respectively, of eq (1); eq (4) and (6) are obtained by x and y differentiations, respectively, of eq (2). Second horizontal derivatives of the flow field are neglected, as is the variability of f.

The neglect of higher order space derivatives of u and v is the most restrictive assumption of the model, and some implications of this are discussed in I. The result of this simplification is a system of equations that retains some effect of horizontal variation; however, solutions at a given point in the horizontal depend only on the two independent variables, z and t. Thus, a four-dimensional problem in (x, y, z, t) is reduced to a two-dimensional problem, and lateral boundary conditions need not be specified. In this way, two of the biggest problems associated with mesoscale modeling are avoided. This concept is the basis for similarity solutions summarized by Greenspan (1968) and for the steady-state study of Benton et al. (1964).

To use the system of equations to forecast w, (through the vertical integral of the forecasts for u_x and v_y), one must specify the geostrophic pattern and K for the duration of the forecast. In this study, the geostrophic field is obtained from 850-mb height data and modified by terrain effects as explained in the next section.

The specification of K is described in I. In brief, an idealized diurnal oscillation of the Monin-Obukhov scale length is specified. Consistent surface-layer profiles are thus obtained for different times of the day. K is arbitrarily given maxima at about 500 m during the midafternoon and at the top of the surface layer during the night. Fortunately, the results are not very sensitive to the values of K above the surface layer.

Boundary conditions specify no flow at the roughness height (assumed to be 1 cm), and the solution of the balance equation is used at 2,000 m. Inital conditions cannot be accurately measured. However, since the solution at any time depends most strongly on the current pressure pattern and eddy stresses and their recent values, it turns out that any initial state close to balanced flow will lead to practically the same result after 2 days of integration. To insure independence from arbitrary initial conditions, we began the integrations 4 days before the verification time. Four-day forecasts at 25 points in the horizontal for each of the nine case studies require 8 min of UNIVAC 1108 computer time.[1] Further modeling and computational details are outlined in I.

3. SELECTION OF CASES

The search for cases was centered over the region of the United States east of the Rocky Mountains and west of the Appalachian Mountains. Selections were made on the basis of marked thunderstorm intensification at night, followed by dissipation the next morning. Subjective evaluations of relevant synoptic charts (stability indices, upper level vertical motions, frontal positions, etc.) could not explain the thunderstorm developments in any of the chosen cases.

Investigation of National Meteorological Center (NMC) weather data transmitted over facsimile circuits for the period from late May 1972 to September 1972 revealed nine periods appropriate for this study. The location and approximate area coverage on radar charts for each of 11 cases within these nine periods is superimposed on the surface synoptic analysis in figure 1. Nine of these 11 cases show thunderstorm development between 0100 and 0200 CST and dissipation between 0700 and 0900 CST; the other two cases concern activity that began during the day and continued through the night and into morning. These two cases were selected for study because of the marked intensification of the thunderstorms during the night.

For the purpose of computing the geostrophic data required by the numerical model, a 20×20 grid extending from 86° to 106°W and from 29° to 49°N was established. As noted by Sangster (1967) and Bonner and Paegle (1970), the surface pressure data, reduced to sea level, is not appropriate for accurate specification of the geostrophic flow above the terrain. Radiosonde pressure-level heights above terrain do not have this deficiency since they are not reduced to sea level. Consequently, the 850-mb chart was chosen for specification of the geostrophic wind field. This pressure level is above terrain at all but two of the gridpoints. The two gridpoints for which the terrain height lies above the 850-mb surface are located on the western boundary of the grid and are some distance from any of the case studies. In summary, for each case there are nine grids of 850-mb data that represent, in 12-hr increments, the 850-mb height field during the 4-day forecast period. Six different terms were computed from this field (u_g, v_g, u_{gx}, v_{gx}, u_{gy}, v_{gy}).

These six terms are required inputs to the numerical model at intervals of the 20-min time step. Since the values are known only every 12 hr, it is necessary to use an interpolation technique to generate values at the 20-min intervals. Newton's interpolating polynomial and the natural cubic spline (Gerald 1970) were tested and

[1] Mention of a commercial product does not constitute an endorsement.

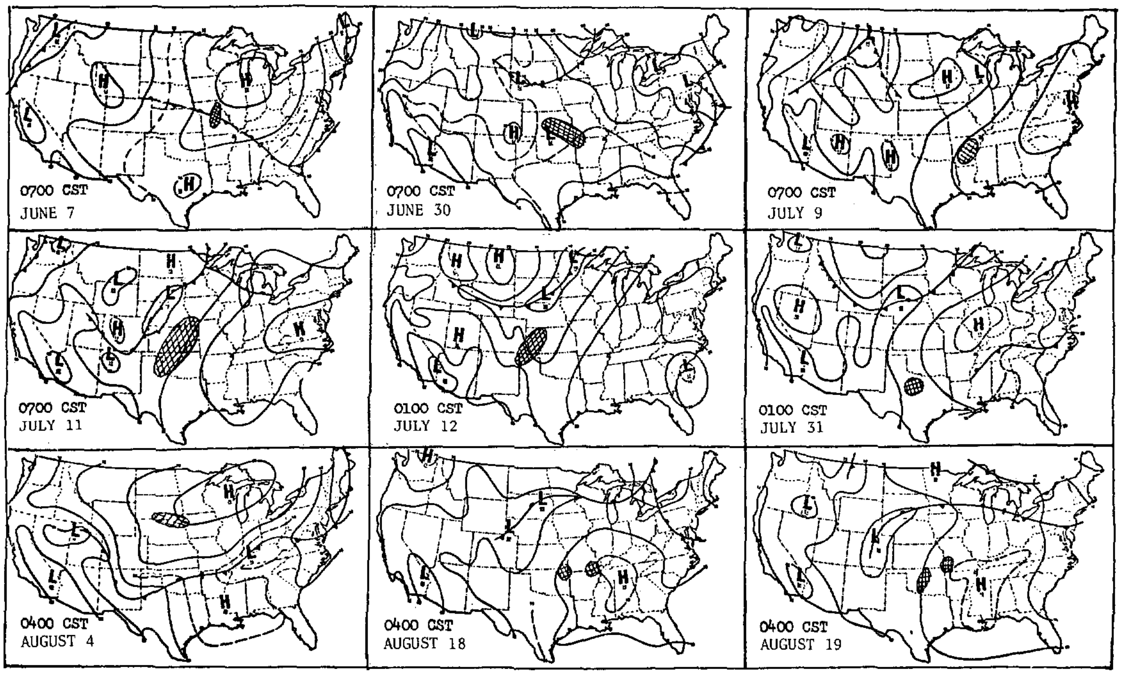

FIGURE 1.—NMC surface analyses and approximate area coverage of radar echoes for the nine periods of study.

compared. The natural cubic spline gave much more reasonable results for the geostrophic components between observation times and was selected for this study.

The 850-mb geostrophic pattern does not give a sufficiently accurate depiction at lower levels, where strong baroclinicity exists as a result of heating and cooling just above the sloping Great Plains terrain. The modification needed at lower levels for the westerly component of the geostrophic wind is

$$u_g=-\frac{g}{f}\left(\frac{\partial z}{\partial y}\right)+\frac{g}{f}\left(\frac{\partial z_T}{\partial y}\right)S^*\ ; \tag{8}$$

for the northerly component of the geostrophic wind, it is

$$v_g=\frac{g}{f}\left(\frac{\partial z}{\partial x}\right)-\frac{g}{f}\left(\frac{\partial z_T}{\partial x}\right)S^* \tag{9}$$

(Sangster 1967, Bellamy 1945).

Here, g is the apparent gravity, $\partial z/\partial y$ and $\partial z/\partial x$ are the horizontal derivatives of the height of the 850-mb surface, $\partial z_T/\partial y$ and $\partial z_T/\partial x$ are the horizontal derivatives of the terrain elevation. S^* is the specific virtual temperature anomaly,

$$S^*=\frac{T^*-T_s}{T_s}\ , \tag{10}$$

where T^* is the virtual temperature and T_s is temperature in the standard atmosphere.

In this model, S^* is not computed from actual temperature data but is specified by

$$S^*=0.03\cos{(\Omega t-4.19)}e^{-z/800}\ \ \text{m} \tag{11}$$

where t, Ω, and z are time, diurnal frequency, and height above terrain, respectively. This specification of S^* models a diurnal surface temperature variation of approximately 20°C. The phase is such that the minimum value for S^* occurs approximately 4–5 hr after local midnight [$(t=0)$ in eq (11)]. These specifications are within reasonable limits (see Bonner and Paegle 1970).

Smoothed terrain height data of McClain (1960) were used for the computations. These are displayed on a 1° grid in figure 2. All horizontal derivatives of this field were computed using a 2° interval. This gives smoothed gradients over a scale of 440 km commensurate with the horizontal resolution available in the facsimile charts.

Figure 3 shows the horizontal Laplacian of the smoothed terrain field. Positive values indicate regions where the drainage effect would tend to produce boundary-layer convergence at night. Negative values indicate regions where the drainage effect would tend to produce nocturnal divergence. Positive values are found over most of the region, but portions of three cases (fig. 1) of nocturnal thunderstorm activity are located over Missouri, where values are negative.

4. SAMPLE CASE STUDY

An example of one of the nine periods chosen for study is presented in this section. Forecast statistics for all nine periods will be summarized in the next section. The radar charts of figure 4 summarize the precipitation events of the period. The activity, which developed in southern South Dakota, is a somewhat weaker but otherwise typical example of the nocturnal thunderstorms chosen for this study. Thunderstorms present in this area at 2340 CST on August 3 were not related to any earlier radar activity. Two-hourly radar summaries show a steady eastward translation of the echoes through the night until 0640 CST on August 4. By 0940 CST on August 4, the activity had disappeared.

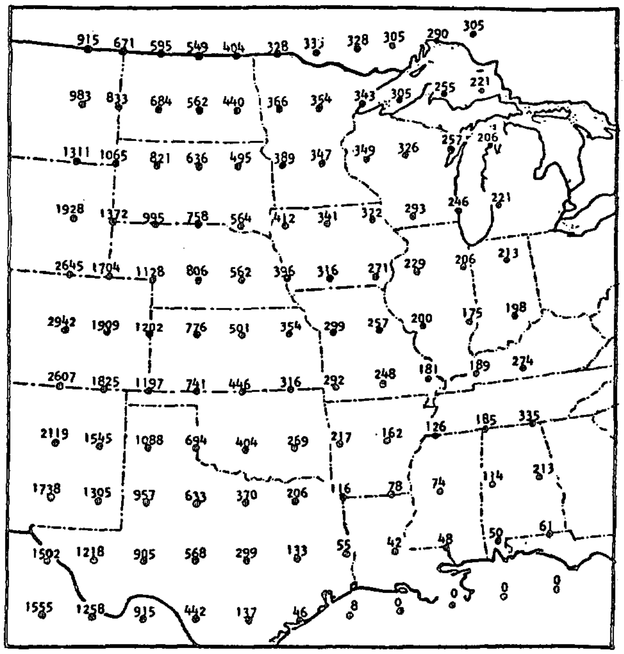

FIGURE 2.—Smoothed terrain heights (m).

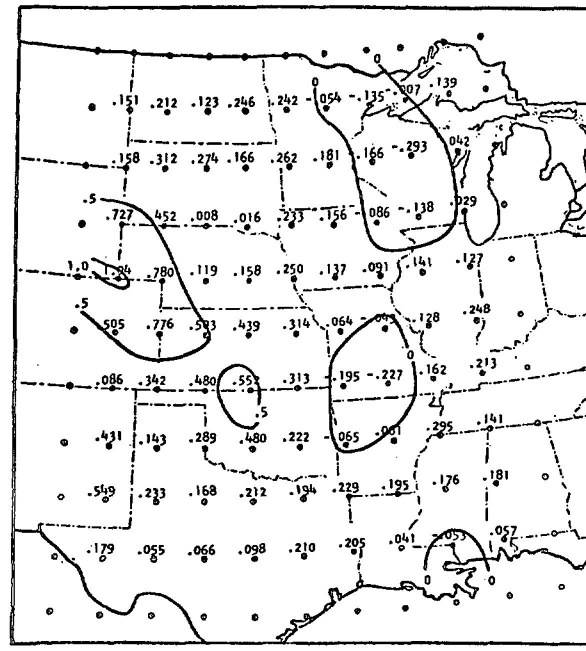

FIGURE 3.—Laplacian of smoothed terrain height field ($m^{-1} \times 10^8$).

There is no apparent source for this activity. The nearest front was 900 km to the south, low-level flow was anticyclonic, and NMC forecasts indicated weak sinking motion at middle tropospheric levels throughout the period.

Other regions of nocturnal precipitation are indicated through Kansas and northern Oklahoma southwestward into southern New Mexico. These areas appear related to activity existing during the previous evening over Colorado, New Mexico, and the panhandle of Texas. This activity spread eastward at more than twice the speed of the 500-mb winds.

In terms of echo tops, the activity associated with this area increased somewhat during the night. However, this increased activity is clearly linked to vigorous upstream activity the previous evening and does not fit the clear-cut nocturnal situations sought in the remainder of the study. Its discussion is included for completeness of the present section.

The 12-hr NMC precipitation forecast verifying at 0600 CST on August 4 (fig. 5) predicts a broad area of precipitation in this area but underforecasts the eastward spread and does not forecast the South Dakota precipitation.

The predictions of the boundary-layer model are summarized in figure 6. At 1900 CST on August 2, about 3 hr before the South Dakota activity began, boundary-layer-induced sinking is indicated for most of the grid. Exceptions are over the gridpoint where the Dakota thunderstorms developed, over eastern Colorado, and on a group of points in the southeastern portion of the grid. Precipition occurred about this time over most of eastern Colorado and in a section of the southeastern quadrant. Precipitation did not occur at several of the gridpoints indicating rising motion in the extreme southeast corner of the grid, and precipitation did occur over portions of Texas despite boundary-layer divergence.

The 0700 CST boundary-layer forecast reflects the eastward progression of the South Dakota echoes toward northwestern Iowa. The sinking indicated for eastern Colorado is consistent with the disappearance of activity in that area, while marked rising motion over Kansas, Oklahoma, and the eastern panhandle of Texas is consistent with the eastward propagation of activity that had been earlier located in Colorado. Based on the boundary-layer convergence alone, the eastern part of the activity would have been forecast to spread into Arkansas instead of Missouri, but the overall eastward shift would be predicted fairly well. Over Louisiana and eastern Wyoming, strong rising is predicted at 0700 CST on August 4, but no precipitation occurred.

5. SUMMARY OF FORECAST ACCURACY

Acceptable upper limits for forecast errors are 3 hr and 2° of latitude and longitude, because the arbitrarily imposed time phasing of the eddy viscosity might not be accurate to less than 3 hr, and the synoptic data resolution is not better than about 200 km. On this basis, the South Dakota and the Kansas, Oklahoma, and Texas thunderstorm occurrences correlate well with boundary-layer convergence patterns. The nonoccurrences over eastern Wyoming and Louisiana do not. Thus, the model forecasts four areas prone to develop nocturnal thunderstorms, and only two verify. Over eastern Wyoming, the atmosphere is highly stable, and the average relative humidity from the surface to 500 mb is less than 45 percent. Over Louisiana, other parameters seem favorable for thunderstorm occurrence, and an explanation for the lack of activity is not evident.

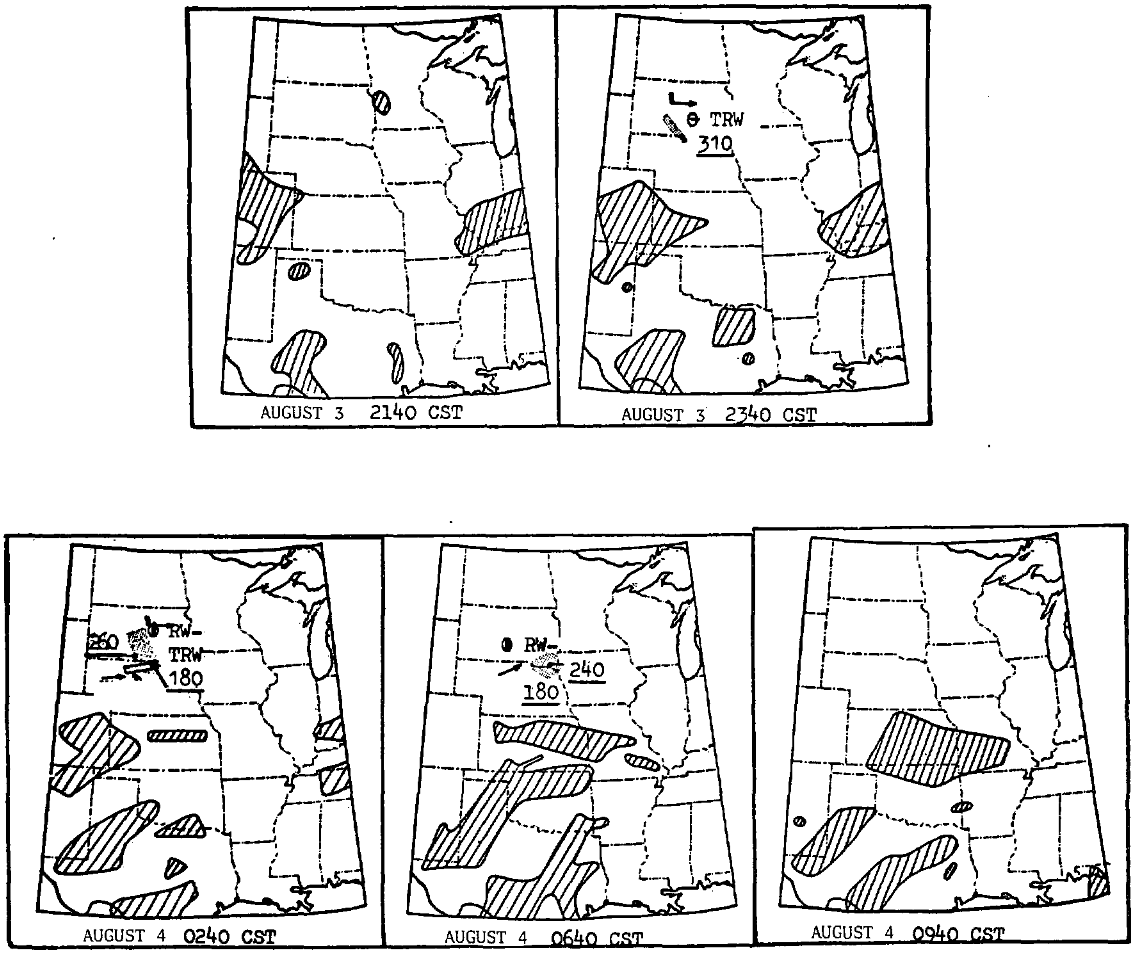

FIGURE 4.—Radar summary charts with precipitation areas delineated by striped zones. TRW denotes thunderstorms, RW denotes light rain shower, underlined numbers are echo tops (10^2 ft), and arrows indicate motion.

A total of 11 thunderstorm areas was found during the nine periods of study that fit the clear-cut nocturnal intensification pattern typified by the South Dakota case discussed above. The time and space phasing between the beginning of such thunderstorm activity and the positive vertical velocities predicted by the model are within acceptable limits in all 11 areas. The time and space phasing between the ending of the thunderstorm activity and the predicted negative vertical velocities are within acceptable limits in only six of the 11 areas. In three of the five areas where the phasing is not acceptable there are gridpoints in the vicinity but beyond the 2° limit, which are in phase with the ending of the activity.

An analysis of the vertical velocity at the top of the boundary layer on charts such as those of figure 6 for all nine periods of study indicates a total of 42 areas in which strong positive vertical velocities (on the order of 1 cm/s or more) had existed for several hours. Thunderstorms occurred within the acceptable time and space range in 28 of these areas. Of the 14 areas that had no thunderstorms, six had conditions otherwise clearly not favorable for their formation, and two had atmospheric conditions which are questionable. Atmospheric conditions were favorable in the remaining six areas, and the vertical velocities appear to be in error because of model limitations

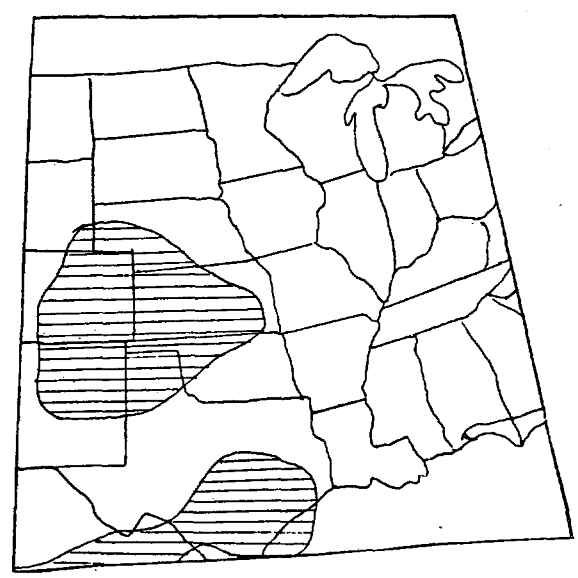

FIGURE 5.—Twelve-hour NMC precipitation forecast (hatched area) valid at 0600 CST, August 4.

or because their effect is compensated by some other factor that we could not discern from the synoptic charts.

The above results clearly indicate that the model could not be used successfully by itself to forecast diurnal

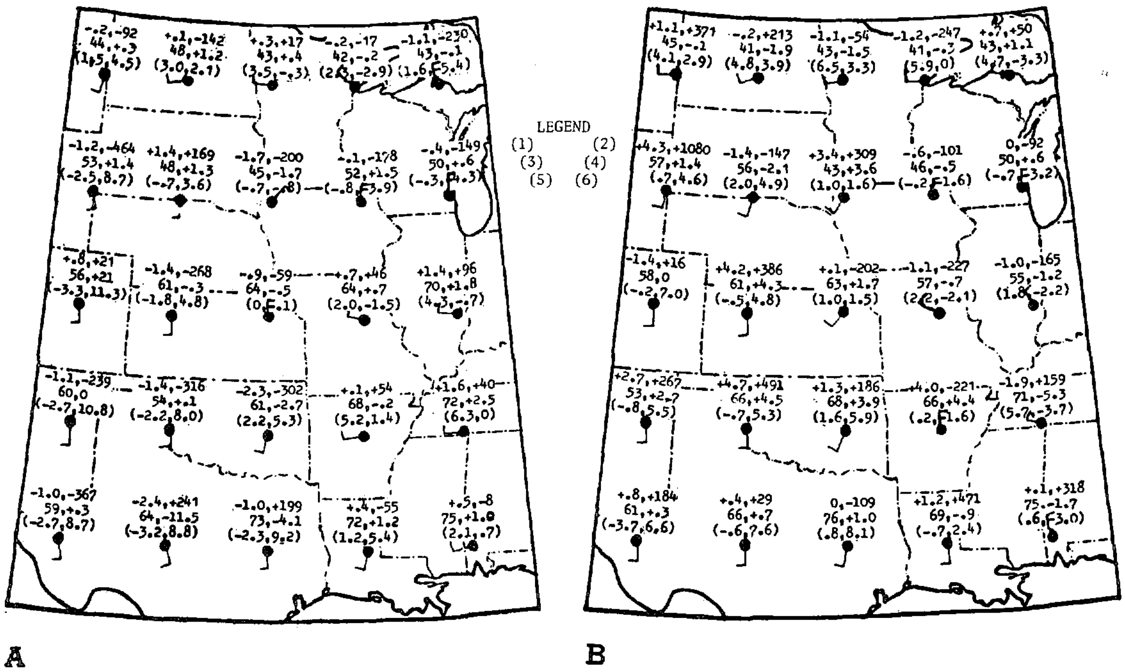

FIGURE 6.—Boundary-layer model forecast valid at (A) 1900 CST, August 3 and (B) 0700 CST, August 4. The grid code legend is (1) current vertical velocity (cm/s), (2) 6-hr vertical displacement (m) due to item (1), (3) surface dew point (°F), (4) current vertical velocity minus that occurring 6 hr earlier, and (5 and 6) the u and v balanced wind components (m/s) at 2 km.

thunderstorm activity in the Great Plains. However, when the model is used in conjunction with synoptic data (mainly stability and moisture indices), the accuracy of the forecast increases substantially. The latter conclusion agrees with the study of Curtis and Panofsky (1958) and indicates the importance of boundary-layer flows in convective phenomena.

6. CONCLUSIONS

A simplified approach to the very complex problems of oscillating boundary-layer winds and diurnal thunderstorm formation has been investigated. The approach involved certain modeling assumptions that result in a simplified system of equations. Part of the difficulty with this system arose because unstable solutions exist in the absence of friction. A certain amount of diffusion can eliminate these instabilities, and it appears that the amount of diffusion used was sufficient, except for one instance. One forecast (out of a total of about 250 that were attempted) experienced this instability, and predicted velocities that were physically impossible.

Considering such model limitations and possible errors in the input data, we find the degree of success met in this approach very promising. The results seem to corroborate the hypothesis that nocturnal thunderstorms might often have their source in boundary-layer processes.

Whether such a model may be useful for operational forecasting remains a question. It should be emphasized that of the many complicating features present in any given case, we have included only those that are of essence in predicting time-dependent horizontal convergence over sloping terrain. Improvements of forecast accuracy could probably be achieved by experimenting with various scales of terrain resolution, by considering moisture and stability indices, and by forecasting the temperature explicitly instead of prespecifying it. These could all be done without losing the basic efficiency of the approach. In operational forecasting, however, the height field of the 850-mb surface would have to be forecast by some numerical tropospheric model, and we have not attempted to assess the impact of the typical forecast errors of such forecast models upon our boundary-layer predictions.

Ultimately, an expansion of a three-dimensional grid-point model of the type developed by Deardorff (1972) would undoubtedly give the best forecasts if sufficient computer power is available and if basic initialization and boundary problems can be overcome.

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